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AUTHOR(S) IRVIN R. LINDEMUTH (X-1)

ROBERT E. REINOVSKY (M-6)

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Irvin R. Lindemuth and Robert E. Reinovsky
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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# EXPLODING METALLIC FOILS AND FUSES: A COMPUTATIONAL MODELING UPDATE

Irvin R. Lindemuth and Robert E. Reinovsky
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

## ABSTRACT

The Los Alamos computational model of exploding metallic foil behavior has been used to analyze and design a wide range of experiments in which exploding metallic foils were driven by the output current of capacitor banks and magnetic flux compression generators. Currents in the experiments ranged from 1 kA–16 MA and foil conduction times ranged from 200 ns–300 $\mu$s. The successes and limitations of the computational model are surveyed.

## INTRODUCTION

A computational model of exploding metallic foil behavior has been developed at Los Alamos [1]. The model couples zero-dimensional hydrodynamics with ohmic heating and electrical circuit equations and uses the Los Alamos SESAME atomic data base library to determine the fuse material's temperature- and density-dependent pressure, specific energy, and electrical conductivity. The model encompasses many previously successful empirical models and offers plausible physical explanations of phenomena not treated by the empirical models. In addition to addressing the electrical circuit performance of an exploding foil, the model provides information on the temporal evolution of the foil material's density, temperature, pressure, electrical conductivity, and expansion and translational velocities. The model has been implemented in a computer code named CONFUSE, a code to COmpute New Foil Utility Studies and Evaluations. Because it is based more-or-less on "first-principles," CONFUSE has provided new insight into the physical behavior of exploding metallic foils and has led to new predictions about the utility of exploding foils as opening switches, i.e., fuses, in pulsed power systems driven by capacitor banks and magnetic flux compression generators. The successes and limitations of CONFUSE are surveyed in this paper.

## CAPACITOR DRIVEN EXPERIMENTS

Initial computational results using the Los Alamos model were presented in an invited paper at the 1985 IEEE Pulsed Power Conference [2]. The foils considered carried currents ranging from 10 kA to 2 MA and had sub-microsecond "burst" times. The computations illustrated the importance of the foil material's trajectory through density-temperature space, and the computations for aluminum foils matched the experimental observations for over 4 $\mu s$ after burst. However, computations for copper foils indicated a feature which has since been encountered in a variety of contexts for both aluminum and copper: the voltage generated and the expansion velocity computed using nominal parameters exceeded significantly that observed experimentally, whereas computations using tamping greater than nominal were in reasonable agreement.

As Fig. 8 of Ref. 1 suggests, one prediction of our model was that the energy-to-burst, or correspondingly, the action-to-burst, depends upon the pressure of the foil material; high pressures, and hence high burst actions and energies, would be expected in either heavily tamped situations or in situations with rapidly rising currents. This prediction was confirmed in experiments performed by Hemsing [3], who discharged a 0.1 $\mu F$, 20 nH capacitive source through 4.3-$\mu m$-thick, 0.23-mm-wide square copper foils tamped by 0.001-in-thick kapton. Burst times of 200-500 ns at currents of 1-4 kA were observed, and the burst actions were determined. As Fig. 1 indicates, burst actions from approximately 1.5 to 2.5 times the value reported by Tucker and Toth [4] were observed, and CONFUSE computations were in reasonable agreement with the observations. Although the variation in burst action can be incorporated into an empirical model, only a first-principles model automatically predicts such variation.

A second prediction of the Los Alamos foil model was that the performance of a foil used as an opening switch, i.e., a fuse, depended upon the thickness of the foil and not merely on the foil's cross-sectional area [1]. Such a prediction is generally beyond the scope of an empirical model. Concurrent with the evolution of our computational model, the Maxwell Laboratories reported increasing voltage with decreasing thickness for aluminum fuses which carried a 23 $\mu s$, 100 kA peak current [5]. The Maxwell experiments made a major contribution to fuse technology by demonstrating high performance with compact fuses made by wrapping a foil-insulator sandwich several times around a small diameter tube. Subsequent CONFUSE modeling [6], as shown in Fig. 2, matched the observations, with a caveat. In the CONFUSE model, the foil material is confined by tampers which are treated as incompressible, so that the entire mass of the tamper must be moved by the expanding foil material. In complex geometries such as used by Maxwell, where the individual layers of foil material may interact, tamping is an ill-defined quantity. The match in Fig. 2 was achieved by adjusting the areal density, $\sigma_T$, of the tamper used in the computations. The value used, 540 $kg/m^2$, probably has no significant physical meaning; lower values would raise the computed voltage in Fig. 2, but the scaling with thickness would remain approximately the same.

High performance copper fuses were demonstrated by McClenahan, et al [7]. By varying the width while maintaining a constant length-to-width ratio, the time to peak voltage was varied from 3 $\mu$s to 6.5 $\mu$s. Currents approaching 2 MA, voltages of 100-240 kV and electric fields of 2-7 kV/cm were observed. Again, because of the method of construction, tamping is an ill-defined quantity in a CONFUSE context. With an appropriate choice of tamping (5 $kg/m^2$), CONFUSE results are in agreement with experiment, as shown in Fig. 3.

Initial fuse experiments aimed at establishing the validity of the Los Alamos model using a CONFUSE-compatible geometry were reported at the Megagauss IV Conference [8]. Laminated fuse assemblies were used as a direct result of our early computations [1] which suggested that the effect of the insulator which surrounded the foil was primarily tamping. Capacitor bank discharges reaching a peak current of 400-600 kA in 4-6 $\mu$s were interrupted partially or totally by varying the aluminum fuse dimensions and bank charge voltage. Computations using the Los Alamos model reproduced the experimentally observed trends which occured as the fuse length or charge voltage was varied. However, the computations underestimated the fuse length at which total current interruption would occur, indicating a need for modification of the theoretically-derived atomic data base which is a central part of the exploding foil computational model. From a technological viewpoint, these experiments demonstrated that a foil-insulator laminated assembly could achieve performance comparable to that achieved in more conventional configurations.

To study fuse performance at long time scales, a series of experiments was performed at Los Alamos. Currents ranged from 400-700 kA and conduction times ranged from 50-150 $\mu$s. The fuses used the laminated construction and interrupted current in 10 $\mu$s or less. Calculations using nominal values correctly predicted the burst time but significantly overestimated the voltage generated by the fuse. However, even though the areal density of the tampers was well defined, it was found that by increasing the value of $\sigma_T$ used in the computations by a factor of 100-1000 above nominal, the computed voltage value would match the observations. In the computations, the increased tamping slows the fuse material trajectory through density-temperature space and moves the trajectory to higher temperature, in a manner similar to that which results from using a decreased length [8]; although only small changes in the trajectory result, the electrical behavior is significantly changed because all material properties vary so rapidly in the relevant density-temperature space.

CONFUSE has been used successfully at the Lawrence Livermore National Laboratory to study electric gun performance [9] and fast fuse opening switches[10]. CONFUSE computations have elucidated the role of both plasma pressure and magnetic pressure in acceleration of the flyer in the electric gun and have proved to be a useful fuse design tool, with predictive capability comparable to that reported here.

## FLUX-COMPRESSION GENERATOR EXPERIMENTS

Our first use of fuses in experiments powered by magnetic flux compression generators (FCG) was to provide a 2 $\mu$s dynamic load for an inductive store system switched by an explosively-formed fuse (EFF) [11]. An experiment in which the 2 MA current delivered to the fuse load was significantly less than the 6 MA expected led to the lengthening of the fuse conduction time and a slowing of the fuse hydrodynamic processes to the point where a correlation between electrical and photographic diagnostics confirmed CONFUSE's hydrodynamic hypotheses [12].

Although it was originally believed that the EFF interrupted current because of mechanical separation of the conductor, it is now believed that the high-explosive extrudes the conductor of the EFF to a point where it ohmically heats rapidly and behaves similar to a conventional fuse. A recent analysis [13] of the experimentally observed resistance increase of the EFF has shown a monotonically increasing resistance at low current levels and a peak followed by a decrease at high current levels. CONFUSE computations which used two-dimensional hydrodynamic computations of the distortion of the conductor to estimate "initial" foil dimensions have qualitatively reproduced the observed behavior and have therefore confirmed the hypotheses that the EFF behaves as a fuse when it has been distorted sufficiently.

Our success with long-time-scale, capacitor-driven, laminated fuse experiments and our successful modeling of the experiments by CONFUSE prompted the design of fuse-switched experiments driven by magnetic flux compression generators. In CONFUSE, an FCG is represented as a time-varying inductance and a time-varying resistance; the FCG inductance is usually determined theoretically by the best available hydrodynamic models, and the resistance is then determined from generator characterization experiments. In all of our computations for capacitor and FCG sources, our ability to predict exploding foil behavior is strongly dependent upon our ability to characterize the entire driving circuit.

Concurrent with our detailed computational effort, we have extended classical fuse analysis to FCG circuits by introducing the concept of an "equivalent action time scale" [14,15]. Our new analysis emphasizes that the initial resistance of a fuse is uniquely determined by the driving circuit in which it appears, so that the fuse's resistance multiplication determines the fuse performance. Our recognition of the role of the equivalent action time scale has led to the redesign of FCGs to reduce the action time without reducing the operation time. The new analysis provides initial estimates of the fuse parameters required and the fuse performance which can be achieved; the estimates provide a basis for a CONFUSE computational design study.

Our first FCG/fuse experiments [14] were driven by a small, relatively inexpensive 49 $\mu$H helical FCG which produced approximately 800 kA from a 25 kA seed current. The fuse was required to carry current for the 180 $\mu$s capacitive discharge which provided the seed current and then for the additional 70 $\mu$s FCG operation time. Typical dimensions of the laminated copper fuses were 10 $\mu$m thick, 56 cm wide, and 40 cm long. The fuse was installed as a single layer cylinder and actually provided part of the structural integrity of the compact FCG/fuse assembly. In essentially all of the ten experiments which were fielded, the current was interrupted by the fuse within a few $\mu$s of the time predicted by CONFUSE, but computations using a nominal value of tamping overestimated the voltage generated. Again, artificially increased tamping in the computations reduced the computed voltage to the experimental value. The amount of increase required was dependent on the generator configuration used. Whereas the nominal $\sigma_T$ was approximately 0.4 kg/m$^2$, a $\sigma_T$ value of 400 kg/m$^2$ matched experiments which produced approximately 1.8 kV/cm. On the other hand, a $\sigma_T$ value of 12 kg/m$^2$ matched high-performance fuses. Fig. 4, where time is measured with respect to initial generator operation, or "crowbar," compares the experimental and computed dI/dt for a high performance fuse (note the very satisfactory timing agreement). Because the system inductance was 350 nH, a peak voltage of about 250 kV, or an electric field of 6 kV/cm, was achieved. In similar experiments, we have achieved a voltage as high as 300 kV, or 7.5 kV/cm.

A small helical/coaxial 0.94 $\mu$H FCG was used to extend our studies of fuse operation to the 7 MA level. The appropriate copper fuse parameters, as determined using CONFUSE, were a 25.4 $\mu$m thickness, a 3.2 m width, and a 20 cm length. Because of the large width required, the copper foil was wrapped with 0.002-inch-thick kapton into a 7-inch-diameter cylinder. Because of the multi-wrap construction, similar to that used by the Maxwell Laboratories, tamping in a computational sense was again undefinable. The four experiments fielded were essentially as predicted by CONFUSE with an appropriate $\sigma_T$, as illustrated in Fig. 5 ($\sigma_T$=100 kg/m$^2$).

Whereas all of our previous experiments used a fuse to totally dissipate the inductively stored energy, we have recently performed an multimegajoule experiment in which a copper fuse was used to transfer current generated by a MK-IX FCG [16] in an inductive store system (66 nH) to a fixed inductive load (24 nH). Fuse dimensions, as determined from CONFUSE computations, were 25.4 $\mu$m thick, 10 m wide, and 28 cm long, and the multi-wrap cylindrical construction was used. The fuse carried current for the 135 $\mu$s charge time and the 200 $\mu$s MK-IX operation time. In the experiment, 15.8 MA of current, or 8.2 MJ, was delivered to the store, and 9.8 MA, or 1.2 MJ, was transferred to the load. The fuse dissipated aprroximately 4 MJ. To the best of our knowledge, the current prior to transfer and the current and energy transferred to the load were the largest ever achieved using a single opening switch element operating on a 10 $\mu$s or less time scale. Because of a capacitor bank malfunction, the FCG seed current was only 80 % of that anticipated, so the fuse used was not an optimal one. Even so, using a $\sigma_T$ of 5400 kg/m$^2$ and the experimentally measured resistance of the surface tracking switch [17] used to couple current to the load, CONFUSE correctly predicted, as shown in Fig. 6, the experimental timing and the rate at which current was delivered to the load, including a surprising double-peaked signal which is attributed to the unique density-temperature trajectory taken by the fuse. The performance indicated in Fig. 6 is deemed adequate for the first stage switch in an advanced Los Alamos 1 MJ foil implosion system [18] which will use a plasma flow switch as a second stage of pulse compression.

## CONCLUDING REMARKS

The CONFUSE computer code which incorporates a first-principles model of exploding metallic foil behavior has become a very useful tool for the design and analysis of foil experiments which have spanned three orders of magnitude in time scale and four orders of magnitude in peak current. Essentially all experimental trends have been successfully predicted computationally, and, in cases where observations differed from computation, an adjustment of model parameters (usually $\sigma_T$) has made possible a close match between experiment and computation. In general, the biggest discrepancy of the computations for fuses is an overestimation of the voltage developed, and hence an underestimation of the switching time. However, we have performed enough experiments and computations to reasonably predict a range of performance which might be encountered, and since the computations generally predict accurately the experimental timing, the "adjusted tamping" provides a reasonably satisfactory design capability. It appears that the necessity to adjust $\sigma_T$ in some instances where $\sigma_T$ is well-defined is related to inaccuracies in the atomic data base which is fundamental to the computational model. On the other hand, the variability of $\sigma_T$ in instances where $\sigma_T$ is not definable may reflect, in part, different effective tamping of the foil material. Theoretical and *ad hoc* methods are being used to modify the atomic data base. We hope that the model will evolve to a point where we will understand in detail why fuse performance is relatively low (2 kV/cm) in some instances and quite high (7 kV/cm) in others, since the former may be unsatisfactory in some applications whereas the latter may be more than adequate.

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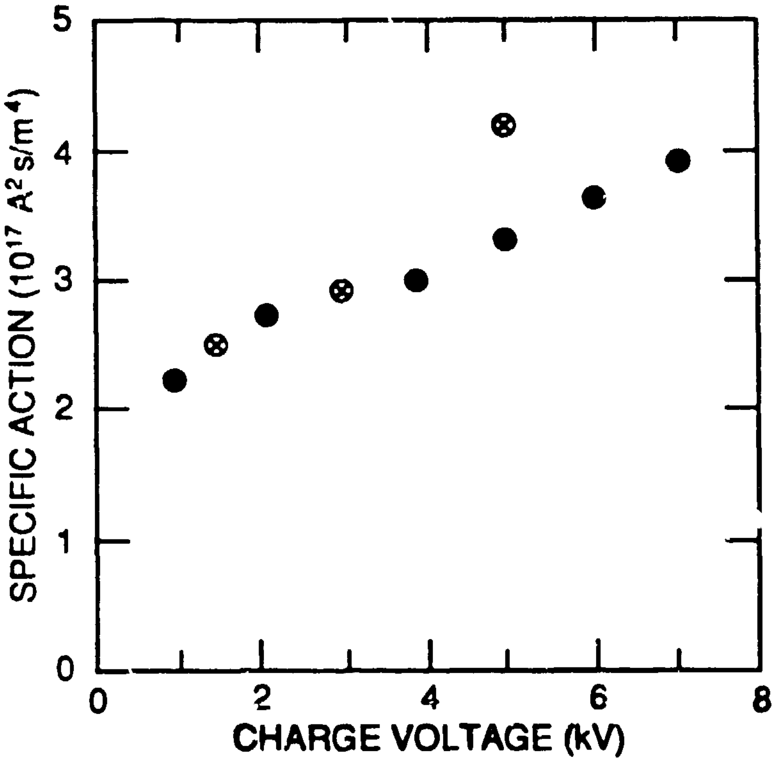


Fig. 1. Specific action-to-burst as a function of charge voltage for the experiments of Ref. 3 (⊗) and CONFUSE computations (•).

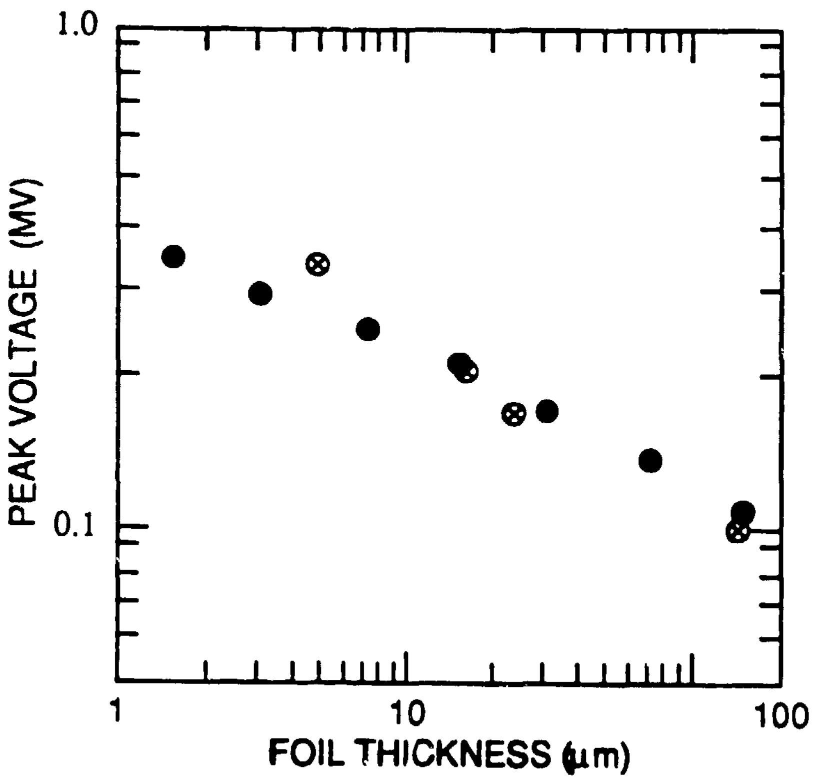


Fig. 2. Peak voltage as a function of foil thickness for the experiments of Ref. 5 (⊗) and CONFUSE computations (•).

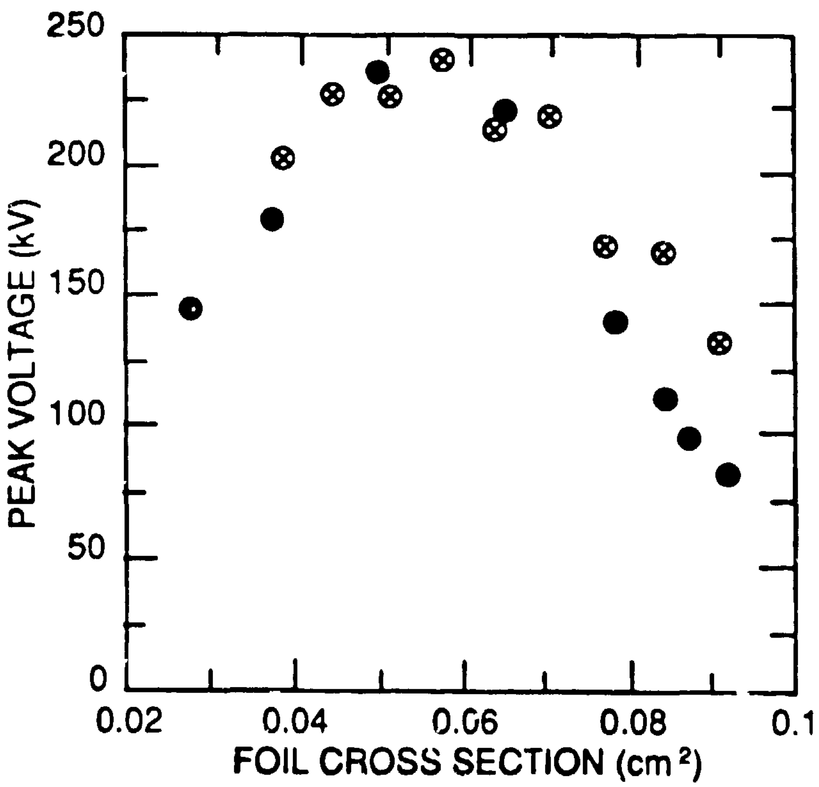


Fig. 3. Peak voltage as a function of foil cross-section for the experiments of Ref. 7 (⊗) and CONFUSE computations (•).

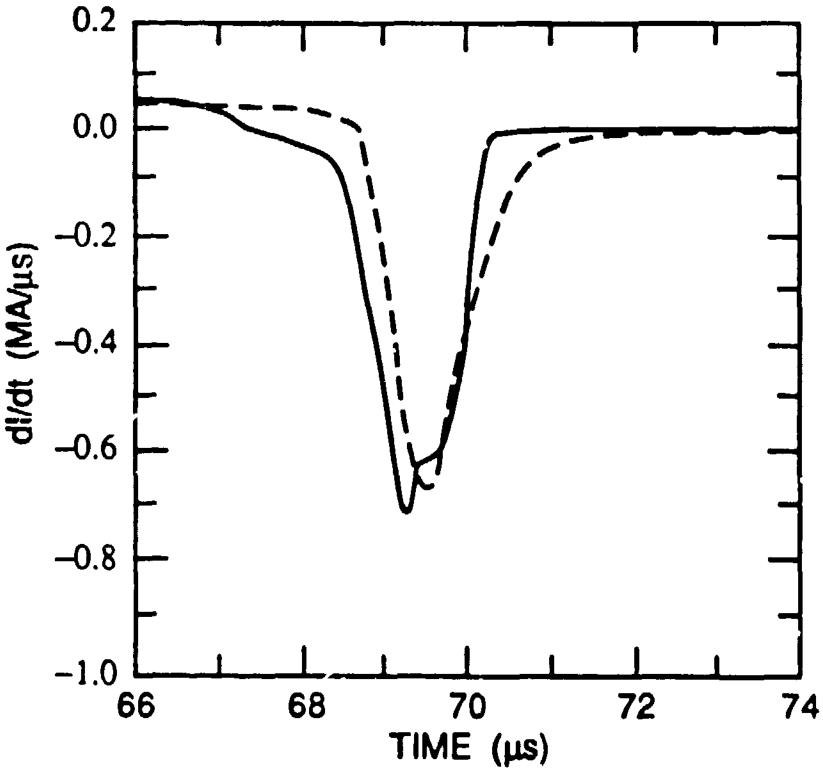


Fig. 4. Fuse current time-derivative for an 800 kA FCG-driven experiment (dotted) and a CONFUSE computation (solid).

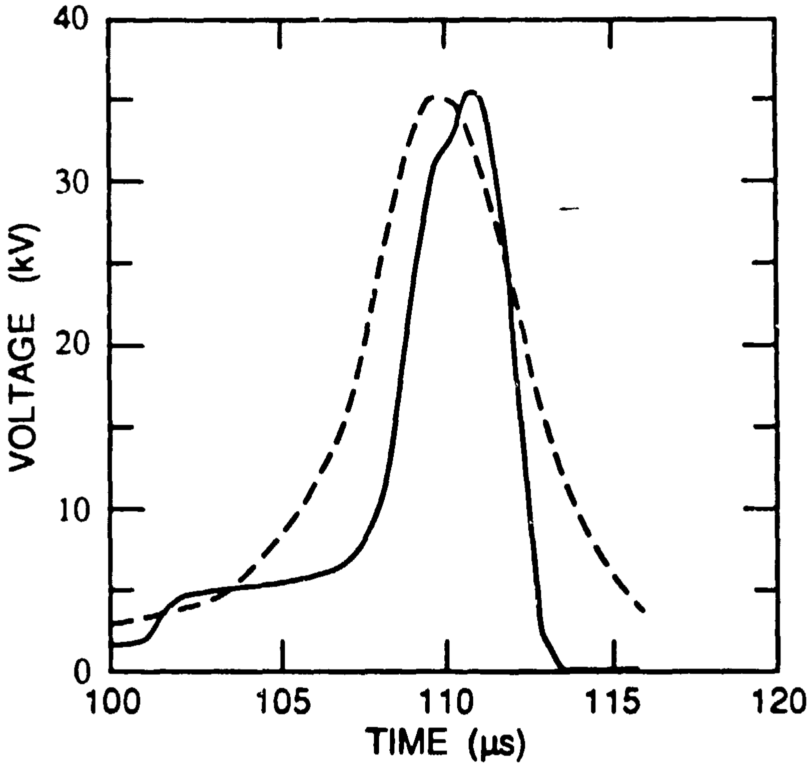


Fig. 5. Fuse voltage as a function of time for a 7 MA FCG-driven experiment (dotted) and a CONFUSE computation (solid).

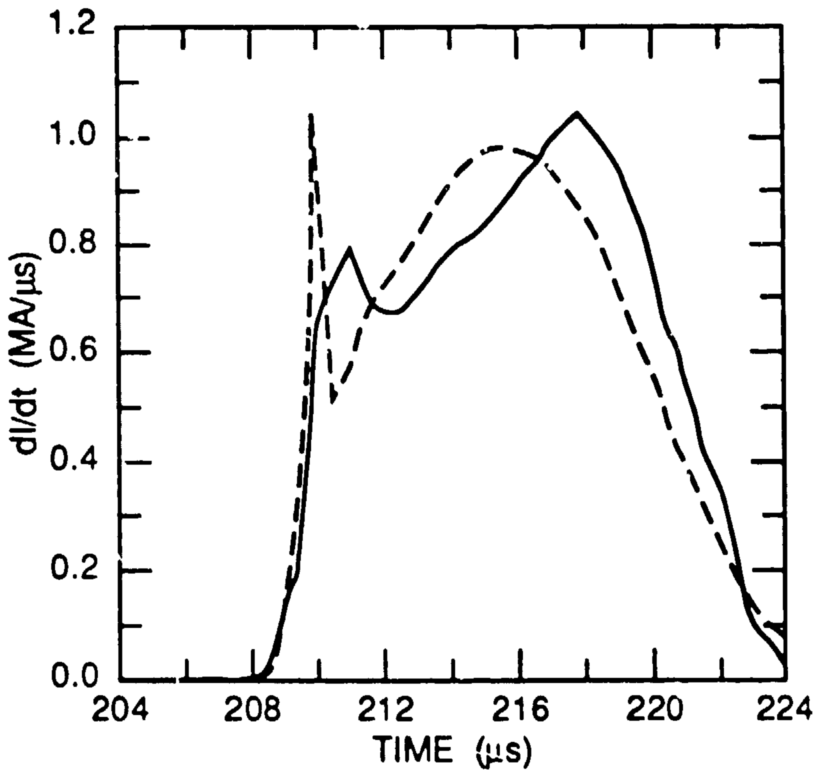


Fig. 6. Inductive load current time-derivative for a 16 MA FCG-driven experiment (dotted) and a CONFUSE computation (solid).